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BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

SUBJECT: Space Tug Operations in Association With the Integrated Program - Case 105-3

DATE: January 9, 1970

FROM: M. H. Skeer

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(NASA-CR-110384) SPACE TUG OPERATIONS IN ASSOCIATION WITH THE INTEGRATED PROGRAM (Bellcomm, Inc.) 30 p

ABSTRACT

The space tug defined in the Integrated Program Plan is a reusable and versatile propulsion module capable of performing varied space operations in support of earth orbital, lunar, and planetary missions. In this memorandum space tug propulsion module tasks, payloads, and velocity requirements are surveyed in some detail and the implications of achieving a versatile tug system considered.

In addition, representative space tug sizes are reviewed with regard to performance of missions in the Integrated Program. Particular emphasis is placed on earth orbit applications and alternate lunar mission modes. A tug of about 50,000 lbs appears to satisfy mission requirements in all areas of the Integrated Program. An 80,000 lb tug can provide greater maneuvering for landing at and launching from out-of-plane landing sites on lunar missions, and in association with an earth orbit/lunar orbit shuttle can land a 50,000 lb base from high elliptic lunar orbit. A small tug on the order of 10,000 lbs can provide limited but worthwhile capabilities in earth orbit and other mission areas.

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MEMORANDUM FOR FILE

INTRODUCTION

The space tug defined in the Integrated Program Plan (reference 1) is a highly reusable versatile propulsion module capable of performing varied space operations in support of earth orbital, lunar, and planetary missions. In this memorandum a broad spectrum of possible space tug tasks, payloads and velocity requirements are considered. Suitability of different space tug sizes for performance of missions in the Integrated Program are discussed.

SPACE TUG CHARACTERISTICS

Space tugs are a class of vehicles which fulfill the need for mobility in the space environment. Potential space tug operations are summarized in Table 1. Earth orbit operations include activities which directly support a space station or base, provide for servicing of independent modules and satellites, and provide logistics from low orbit to synchronous orbit space stations. In association with a lunar orbit base or earth orbit/lunar orbit shuttle, the space tug can deliver crew to and from the surface, transfer large payloads to the surface from lunar parking orbit, and provide surface to orbit rescue capability. The tug could also be utilized as a 4th stage on Saturn V to deliver large payloads to the moon before availability of a earth orbit/lunar orbit shuttle. With a planetary spacecraft the tug can perform midcourse correction maneuvers and major maneuvers such as mission module escape from planetary parking orbit, and retrobraking of earth return payload into highly elliptical earth orbit. (These functions could alternatively be performed by the main planetary propulsion system.) In a dual planetary spacecraft mode the tug could provide rescue capability between the two spacecraft in the event of main propulsion system failure.

TUG PAYLOADS AND MISSION PECULIAR EQUIPMENT

The core of the space tug concept is a propulsion module which must be adaptable to a wide range of payloads and can be modified to suit specialized mission requirements.

Tables 2 and 3 summarize projected space tug payloads and mission peculiar modifications, respectively. Many mission applications would require incorporation of a crew capsule nominally designed to support a crew of up to 6 for several days to several weeks. In association with the propulsion module the capsule might be required to serve as a facility for in situ satellite servicing, a cabin for crew transport between low earth orbit and a geo-synchronous orbit space station, a lunar surface to orbit transfer vehicle, and a short term lunar surface base. On planetary missions the capsule could be propulsively braked into elliptical earth parking orbit for subsequent retrieval by the space shuttle, and on planetary missions in which the dual spacecraft mode is employed the capsule could be used for crew rescue.

For some missions unmanned mainpulators could be substituted for the crew capsule. Small unmanned manipulators on the order of 1000 lbs (reference 2) could accomplish basic servicing tasks in situ or pick up a satellite for servicing at the station. A cargo module could alternately be utilized for transport of large unmanned payloads.

Lunar surface operations would require additions to the tug comprised of landing gear and radar, and unloading equipment for handling of surface payloads. Tugs in association with planetary spacecraft may require refrigeration for long term propellant storage.

Space tug propulsive capability could be extended by utilization of staged tugs. Alternately, tug designs may incorporate expendable strap-on tanks - this possibility has not been studied here.

PROGRAM CONSTRAINTS

The space tug is subject to interface constraints imposed by other hardware elements of the Integrated Program. The space tug is to be launched in the space shuttle within a payload container which is currently conceived as having nominal dimensions of 15 ft diameter and 60 ft length. A 22 ft diameter container bulge of 30 ft length is however being considered for incorporation of larger diameter payloads (reference 3). Space shuttle payload weight at launch is limited between 25 and 50 K. The tug could however be launched off loaded, if gross weight exceeded this limit.

For space operations the tug would be refueled either from the shuttle or at a tank farm on orbit. Some operations such as satellite servicing require that the tug be capable of operating essentially as a third stage of the space shuttle. This could be necessary if for example the satellite were

inaccessable to the space station due to excessive plane change ΔV; the tug would then be launched directly into the orbit plane of the satellite by the shuttle. In this circumstance the tug might have to be off loaded to meet the shuttle payload weight limitations so that impulse velocity would be somewhat reduced compared to launch from a space station. The tug would reenter the shuttle payload bay for return to earth.

The lunar landing mission would size the engine and govern throttling requirements, and could also impose the controlling structural load environment. Long term storage for planetary missions if included as a basic design consideration would likely govern the thermal isolation system design.

PERFORMANCE CONSIDERATIONS

Space tug operations involve low ΔV maneuvers in the vicinity of space stations, high ΔV maneuvers for satellite servicing, placement, and retrieval, and intermediate ΔV for lunar landing applications and planetary mission payloads. Operational modes and performance consistent with these mission classes are considered in the ensuing discussion. LO_2/LH_2 propulsion system, with a specific impulse of approximately 460 secs, is assumed. Propellant fractions, λ (ratio of useful propellant to stage weight), between .80 and .85 are presumed depending on the size of the tug system.

High ΔV Maneuvers - Transfer from a space station to a satellite in another orbit generally involves changing altitude, equatorial inclination, and the line of nodes. Although individual orbit altitudes and inclinations remain essentially fixed with time, as noted in Reference 4, differences in nodal regression rates between the station and satellite can cause nodal alignment to vary substantially with time (Figure 1 shows the nodal regression rate as a function of altitude and orbit inclination).

Figures 2 and 3 respectively show contours of constant ΔV from a space station and the time dependency of ΔV for various satellite locations relative to a space station. As seen in figure 3, some satellites would be accessable for long periods but at infrequent intervals while other satellites would be accessable at frequent intervals but for short periods. A special situation arises between satellites and stations at common altitudes and inclinations such as in sun-synchronous orbit where no relative nodal regression occurs. In such cases major ΔV maneuvers (plane change) still are required if the ascending nodes are not aligned.

Figures 2 and 3 indicate that sizable transfer velocities may be required for satellite servicing and other earth orbital operations. Since tugs are reusable, they must achieve twice the one-way velocities indicated. Some high velocity missions would be achievable only by tug staging.

In general as a result of ΔV time dependency additional constraints are placed on orbital transfer, i.e. servicing of satellites must wait until an opportune time for transfer has arrived. If satellite down time must be minimized either 1) the satellite orbit must conform to one that is frequently accessible for servicing with a reasonable ΔV, 2) a spare satellite must be provided, or 3) the satellite must be serviced directly from earth with the space shuttle rather than from the space station.

Figures 4-6 show the relationship between ΔV and space tug weight for representative sets of payloads and operational modes. The ordinate gives normalized tug weight (per 1000 lbs of payload) and can be scaled linearly for other payloads. Figures 4 and 5 show respective stage weights required for placement and retrieval of payload (typically unmanned satellites) and figure 6 gives the weight for round trip payload (such as a manipulator utilized for in situ satellite servicing). Three modes are considered. Mode I employs a single tug for the round trip. Mode II employs a pair of tugs which are series staged. Here Tug A delivers Tug B and payload to an intermediate velocity and returns to the station. Tug B delivers and retrieves payload to the required velocity and returns to the space station. Mode III is a perturbation of Mode II. Tug A is refueled at the station and retrieves the fuel depleted tug B and payload at an intermediate orbit. The technique of each mode is schematically indicated in figure 7.

Tugs can also launch unmanned planetary payloads in modes similar to those employed for earth orbit operations (references 5 and 6). If the forward tug is not recovered substantial increases in payload or velocity can be achieved. Figures 8 and 9 show tug weight per 1000 lbs of payload weight versus velocity for recoverable and non recoverable tugs operating in single and staged tug modes.

Intermediate ΔV Maneuvers - The space tug is to be utilized for delivery of crew and payload to the lunar surface from a space station or lunar shuttle in lunar orbit, and also for crew departure from the lunar surface. One way ΔV's of approximately 7000 fps are required for in plane descent and ascent trajectories to and from low circular lunar orbits. As an alternative to low circular orbits, elliptical parking

orbits have been cited as being advantageous for reducing lunar shuttle gross weight and performance sensitivity (reference 7). This would require the tug to achieve up to 8800 fps for in plane landing. The ΔV difference between circular and elliptical orbit could however be offset if plane change maneuvers for transfer to or from out-of-plane landing sites are required.

The plane change penalty could have a significant affect on tug size, or alternatively, tug ΔV capability could significantly restrict out-of-plane launch or landing. A base in polar lunar orbit has been cited as a potential goal of the Integrated Program. The polar orbit is coplanar with surface sites twice a month (as the moon rotates under the orbit). All landing sites can be reached with the minimum velocity but substantial penalties can result for emergency return or curtailed staytimes of less than two weeks. Figure 10 (reference 8) shows plane change ΔV (above coplanar ΔV) for launching into a 60 nmi circular orbit as a function of launch window size. For example, a launch window of $\pm$ 1 day requires a total ΔV of approximately 8600 fps compared to 7000 fps for in plane launch. This is increased to over 10,000 fps for a $\pm$ 2 day window. To achieve the increased velocity for rescue without inordinate tug sizing penalties, tugs could be staged. The landed tug could abort to an intermediate orbit and be retrieved by an orbital tug which supplies the remaining plane change velocity.

Elliptical parking orbits at the moon are potentially attractive for operations in association with the lunar orbit/earth orbit shuttle. A more optimum staging results for earth orbit to lunar surface logistics which reduces lunar shuttle size sensitivity to λ, but in turn increases the size of the tug. For a 24 hour parking ellipse in plane landing ΔV is 8600 fps versus 7000 fps from low circular orbit. However, if extensive plane change is required the elliptical orbit can be more economical. Maximum plane change at apoapsis is only 750 fps so that complete landing site capability can be achieved for a one way velocity of 9400 fps vs 14000 fps for low circular orbit.

Large payloads comprised of a lunar surface base and support systems would be delivered at times of minimum ΔV. Thus plane change penalties would apply principally to crew logistics.

Capability of the tug propulsion module as a fourth stage on Saturn V for delivery of payload to lunar orbit prior to availability of the earth orbit/lunar orbit shuttle is shown in Figure 11 (reference 9).

Low ΔV Maneuvers - Low ΔV maneuvers could be required for orbit keeping of large space stations in earth and lunar orbits, placement and servicing of free flying experiment modules in orbits essentially the same as that of the space station; and possibly midcourse correction for large planetary spacecraft. Figure 12 shows propellant weights and payload relationships for the range of ΔV up to 2000 fps. As an example, propellant weight to provide a 500 fps space station orbit keeping capability is 3.3% of gross weight. (A 1 million lb space base would require 33,000 lbs of propellant.) A planetary spacecraft with various staging maneuvers en route would typically require midcourse propellant of from 2% to 4% of initial weight in earth orbit.

SPACE TUG SIZING CONSIDERATIONS

Space tug sizing requirements have strong interaction with other hardware elements in the Integrated Program and the operational modes utilized. Table 4 cites the factors that are possible considerations in sizing the tug.

Tug velocity capabilities for the classes of mission discussed are summarized in Table 5. Herein tug sizes at 10 K, 50 K and 80K are examined. The 10 K size is arbitrarily selected - the stage could be even smaller. The 50 K tug is nominal for the Integrated Program, and the 80 K tug is appropriate to elliptical lunar parking orbit operations, cited in Reference 7. λ's of .80, .80/.85, and .85 are assumed for the 10 K, 50 K and 80 K stages respectively. The 10 K tug design is conceptually similar to the small upper kick stages cited in Reference 10. From these data λ on the order of at least .8 should be achievable. From studies of stages in the 30 K to 110 K range (references 11-14) λ's in excess of .85 would be realized for the larger tugs. Additional systems on the tug (Table 3) could however degrade λ to .80.

The 10 K tug could be utilized for operations in the vicinity of the stations in earth and lunar orbits. A single 10 K tug with a crew capsule could provide transportation for orbits separated by up to about 5000 fps ΔV. Tugs operated in staged modes could achieve up to 18,000 fps (36,000 fps round trip) for payloads of 1000 lbs. A small tug delivered to the lunar surface fully loaded or fueled on the surface by subsequent tug flights could provide a capability for lunar surface to orbit rescue for a crew of 6 and could be utilized as an operational lunar flying vehicle. On a dual mode planetary mission the 10 K tug could provide crew rescue capability, and provide earth capture ΔV for a crew capsule. (Capsule weight is assumed between 5 and 10 K).

The 50 K tug is capable of delivering a 50 K base to the surface from low circular lunar orbit. The 50 K tug can also transport a 5 K crew capsule to the lunar surface and back to orbit with sufficient margin for a $\pm$ 1 1/2 day launch window (9600 fps one way ΔV). A fully loaded stage on the surface could provide abort directly to earth orbit. As a fourth stage on Saturn V, between 90 K and 95 K could be inserted in low circular lunar orbit. On manned planetary missions the 50 K tug could brake a 50 to 100 K mission module into elliptical earth capture orbit and several tugs (2 to 4 depending on mission class) could achieve mission module planetary escape in lieu of main propulsion. In earth orbit, transfers between orbits separated by 8000 to 10,000 fps could be achieved by a single recoverable stage for placement, retrieval and servicing of small satellites. Transfer ΔV's from 16,000 to 20,000 fps could be obtained by staging. (The velocity capability of the staged mode is notably higher than that available from a single-stage earth orbit/lunar orbit shuttle.) Table 6 shows space tug payload for selected unmanned planetary missions utilizing series staging. Completely reusable and partially reusable (i.e. one tug expended) modes are compared with TIIID/Centaur (reference 15) for representative velocities.

The 80 K tug could deliver 50 K to the lunar surface from 24 hr elliptical lunar orbit. With a 5 K crew capsule a recoverable tug could achieve 10,600 fps each way. Because of the reduced plane change penalties associated with elliptical orbits (750 fps maximum) this is sufficient ΔV for an open abort launch window ($\pm$ 7 days). An off loaded stage on the surface could achieve direct abort to earth. Approximately 100 K could be injected into low circular lunar orbit by the tug as a fourth stage on Saturn V. For earth orbit operations the 80 K tug essentially extends 50 K tug capability to operations with larger payloads. Performance with small payloads is primarily dependent on stage λ and is independent of stage size per se.

SPACE TUG SUMMARY

Satellite servicing missions can place major ΔV requirements on the space tug. The tradeoff between servicing from a space station or directly from earth via space shuttle must be considered. Staged tugs provide synchronous orbit (and higher ΔV) capability and can deliver sizable payloads on unmanned interplanetary missions.

A large tug on lunar missions can provide substantial out-of-plane maneuvering and can land a large base from high elliptic lunar orbit. On planetary missions the tug can be utilized for earth return and capture maneuvers in lieu of the main propulsion system. Where dual planetary spacecraft are utilized the tug can provide rescue capability between spacecraft.

As a fourth stage on Saturn V tugs in the 50 K - 80 K class can deliver in excess of 90 K to low circular lunar orbit. Performance is relatively insensitive to stage weight.

For high performance O_2/H_2 stages:

a. A 50-80 K tug satisfies earth orbital, lunar, and planetary mission requirements of the Integrated Plan. The lunar mission presently governs tug sizing requirements.

b. A small tug provides worthwhile capabilities for earth orbit and planetary missions (the latter only if long term propellant storage or transfer is available).

M. H. Skeer

1013-MHS-kle

Attachment

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TABLE 1
SPACE TUG OPERATIONS

MISSION AREA	OPERATIONS

EARTH ORBIT	• SPACE BASE SUPPORT ACTIVITIES
	  • SPACE BASE ASSEMBLY
	  • TRANSFER PAYLOADS FROM SS AND NUCLEAR SHUTTLE
	  • ORBIT KEEPING
	  • INSPECTION
	• SATELLITE PLACEMENT AND RETRIEVAL
	• IN SITU SATELLITE SERVICING AND INSPECTION
	• SATELLITE AND INTERPLANETARY SPACECRAFT LAUNCH
	• CREW SHUTTLE TO SYNCHRONOUS ORBIT

LUNAR	• LUNAR SURFACE TO ORBIT CREW TRANSFER • DELIVERY OF LUNAR SURFACE BASE AND OTHER SURFACE PAYLOADS • SATURN V 4th STAGE • RESCUE • TUG CAPSULE AS SHORT TERM BASE ON SURFACE
PLANETARY	• MIDCOURSE CORRECTION MANEUVERS • PLANETARY ESCAPE AND EARTH CAPTURE MANEUVERS • RESCUE (DUAL SPACECRAFT MODE)

TABLE 2
SPACE TUG PAYLOADS

MISSION AREA	PAYLOADS	WEIGHT (LBS)
EARTH ORBIT	• CREW CAPSULE *	5,000 - 10,000
	• MANIPULATOR	1,000
	• SMALL SATELLITES	1,000 - 3,000
	• LARGE SATELLITES	5,000 - 25,000
	• SPACE STATION MODULES	100,000
LUNAR	• CREW CAPSULE *	5,000 - 10,000
	• LUNAR SURFACE BASE	50,000
	• CREW CAPSULE BASE *	10,000
	• LUNAR SURFACE MOBILITY	5,000
PLANETARY	• CREW CAPSULE *	5,000 - 10,000
	• PLANETARY SPACECRAFT	1,000,000
	• MISSION MODULES	50,000 - 100,000

* A 3 MAN/50 DAY STAYTIME GARRET SHELTER LUNAR BASE (REFERENCE 16) WEIGHS APPROXIMATELY 6800 LBS., EXCLUSIVE OF EXPERIMENTS AND MISSION EQUIPMENT. OF THIS, BASE DRY WEIGHT IS APPROXIMATELY 4000 LBS. AND EXPENDABLES WEIGHT IS 2800 LBS. 1650 LBS. OF EXPENDABLES IS LO_2/LH_2 FOR FUEL CELL OPERATION IN SUPPORT OF SCIENCE EXPERIMENTS AND MOBILITY SYSTEMS. A MINIMUM LOGISTICS CAPSULE OF SIMILAR DESIGN CAPABLE OF SUPPORTING THREE TO SIX MEN FOR UP TO SEVERAL HOURS TO SEVERAL DAYS WOULD WEIGH APPROXIMATELY 5000 LBS. INCLUDING CREW SYSTEMS.

TABLE 3

SPACE TUG MODIFICATIONS

MISSION AREA	MODIFICATION KITS
EARTH ORBIT	• SERVICING KITS • DOCKING STRUCTURE • STRAP ON TANKS
LUNAR	• LANDING GEAR • LANDING SYSTEMS • LOADING EQUIPMENT
PLANETARY	• REFRIGERATION? • ENLARGED RCS SYSTEM?

TABLE 4

SPACE TUG SIZING CONSIDERATIONS

MISSION AREA	POSSIBLE SPACE TUG SIZING CONSIDERATIONS
EARTH ORBITAL	• SATELLITE SERVICING ΔV REQUIREMENTS • TUG STAGING • SPACE SHUTTLE PAYLOAD BAY SIZE LIMITS • ORBIT KEEPING REQUIREMENTS.
LUNAR	• SURFACE BASE WEIGHT • RESCUE REQUIREMENTS • TUG STAGING (MULTIPLE TUGS AVAILABLE?) • ΔV TRADEOFF BETWEEN LUNAR ORBIT SHUTTLE AND SPACE TUG
PLANETARY	• TUG VS. MAIN PROPULSION SYSTEM FOR MIDCOURSE CORRECTIONS • TUG VS. MAIN PROPULSION SYSTEM TO RETURN MISSION MODULE • UNMANNED PLANETARY PAYLOAD SIZE AND ΔV REQUIREMENTS

TABLE 5

SUMMARY OF TYPICAL SPACE TUG ΔV CAPABILITY

	MISSION	PAY-LOAD (1000 LBS)	MODE	SPACE TUG ΔV (fps) 10K TUG λ=.8	50K TUG λ=.8	50K TUG λ=.85	80K TUG λ=.85	COMMENTS
EARTH ORBIT	CREW CAPSULE ROUND TRIP	5	I	5600	9600	11000	11900	TUG PROVIDES THIS ΔV EACH WAY ON ROUND TRIP
			II	8100	12600	14300	15300	
			III	11200	16800	19100	20000	
	SATELLITE SERVICING MANIPULATOR ROUND TRIP	1	I	9600	11300	13200	13400	
			II	12600	14500	16800	17000	
			III	16800	19000	21400	21600	
	SATELLITE PLACEMENT	1	I	11100	11400	13700	13800	
			II	14200	14900	17500	17600	
			III	18200	18900	22000	22100	
		25	I	3700	8400	9600	11000	
			II	6000	11800	13500	14900	
			III	6700	14500	16400	18500	
	STATION KEEPING	1000		120	600	650	1100	
LUNAR	CREW CAPSULE ROUND TRIP/ CIRCULAR ORBIT (PLANE CHANGE AVAILABLE)	5	I	—	9600 (± 1 day)	11000 (±3 days)	11900 (± 4 days)	TUG PROVIDES THIS ΔV EACH WAY ON ROUND TRIP
			II	8100 (±1day)	12600 (± 6 days)	14300 (±7 days)	15300 (±7 days)	
	CREW CAPSULE ROUND TRIP/ ELLIPTICAL ORBIT (PLANE CHANGE AVAILABLE)	5	I	—	9600 (±4 Days)	11100 (± 7 days)	11900 (± 7 Days)	
	NON RECOVERABLE SURFACE BASE	50		—	7600	8300	11000	TOTAL ΔV
	RESCUE CAPSULE (ASCENT PAYLOAD ONLY) FULLY FUELED ON SURFACE	5		11300 (± 3 days)	19300 (RETURN TO EARTH ORBIT)	22000 (RETURN TO EARTH ORBIT)	23700 (RETURN TO EARTH ORBIT)	
PLANETARY	UNMANNED SPACE-CRAFT LAUNCH	SEE TABLE 6		→	→	→	→	TOTAL ΔV
	MISSION MODULE RETURN	100		1100	4600	5000	6900	
	CREW CAPSULE RETURN OR RESCUE	5		11200	19200	22000	23800	
	MIDCOURSE COR-RECTION OF PLANETARY SPACECRAFT	1000 (IWIEO)		240	1200	1300	2200	

TABLE 6

SPACE TUG PAYLOAD FOR SELECTED
UNMANNED PLANETARY MISSION
(SERIES STAGING/MODE II)

MISSION	V_C	V_∞	ΔV_I^*	TIIID CENTAUR (DIRECT)	50K SPACE TUG SERIES STAGING (MODE II) (λ=.80 - .85)	
					COMPLETELY RECOVERABLE	ONE STAGE NONRECOVERABLE
MARS	37.8	0.113	12.5	10.0	19.6 -33.3	44.3 - 52.0
VENUS	37.6	0.106	12.3	10.2	21.2 -34.8	45.4 - 53.2
MERCURY (VENUS SWINGBY)	38.6	0.138	13.3	8.2	12.8 -27.0	39.4 - 47.5
JUPITER	46.1	0.293	20.8	3.2	–	12.5 - 17.3
SATURN (JUPITER SWINGBY)	46.6	0.301	21.3	3.0	–	11.4 - 15.7
SOLAR SYSTEM ESCAPE	54.1	0.410	28.8	–	–	0.8 - 4.7

*300 FPS GRAVITY LOSS ASSUMED
**REFERENCE 15

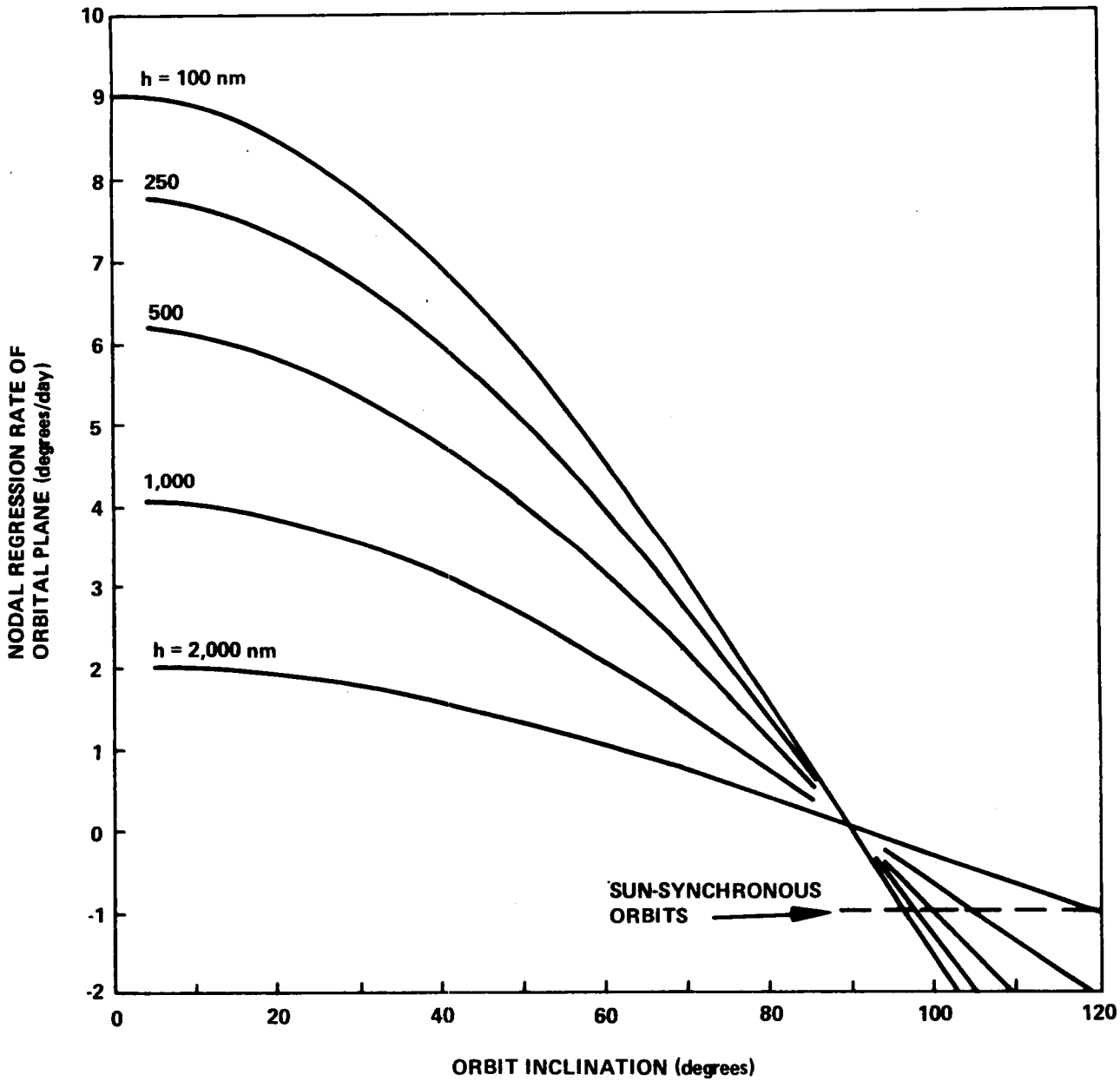
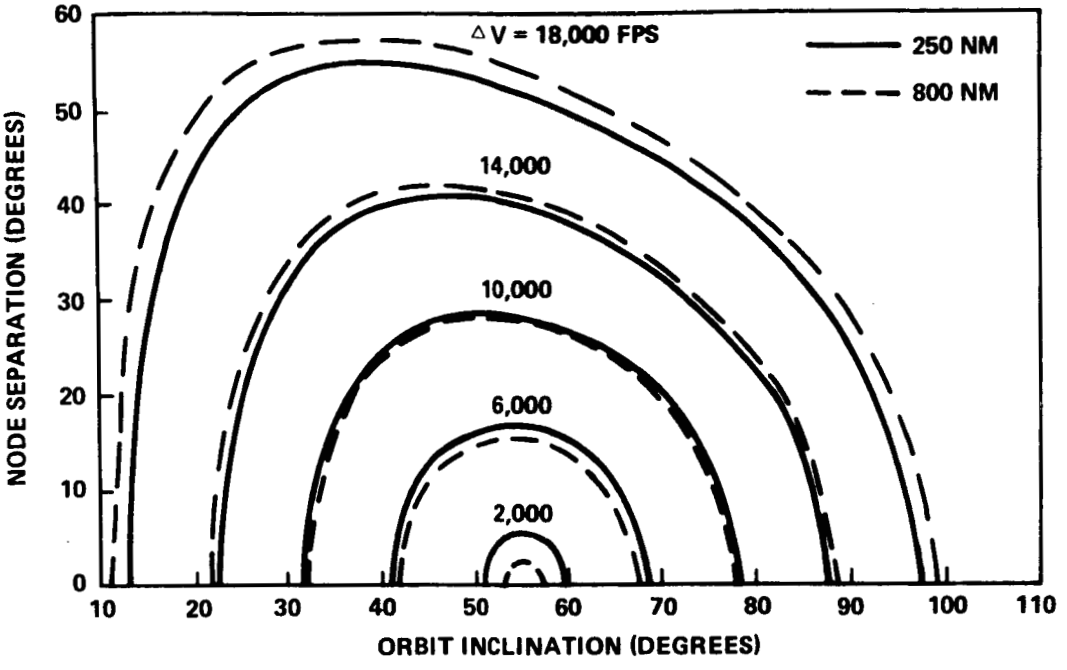
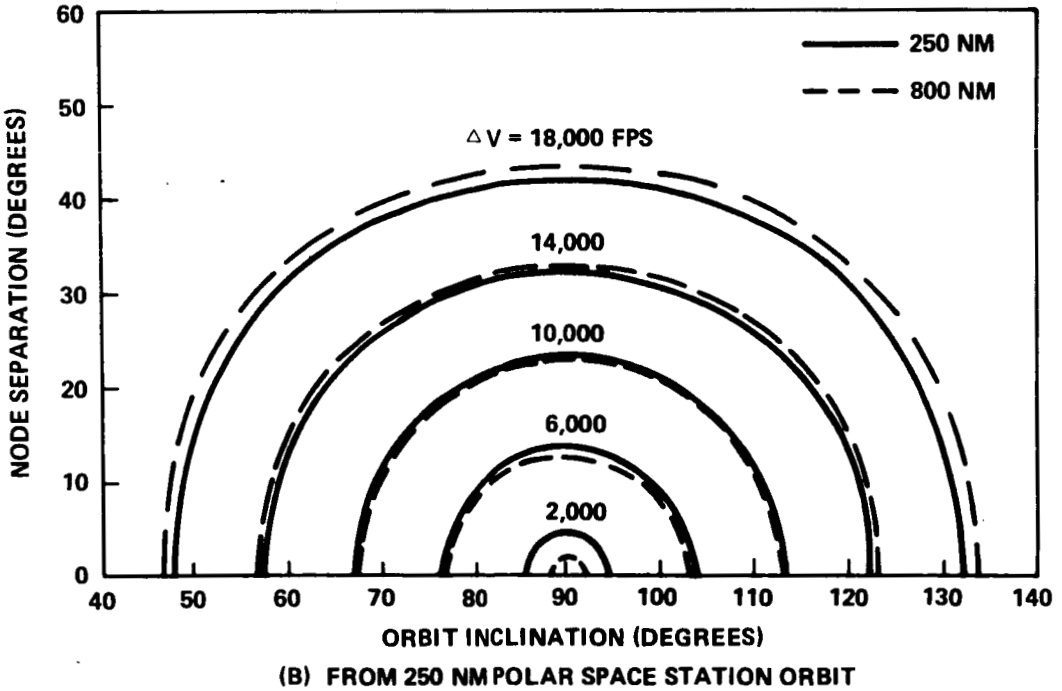


FIGURE 1 - ALTITUDE AND INCLINATION EFFECTS ON NODAL REGRESSION RATE OF CIRCULAR ORBITS (REFERENCE 4)



(A) FROM 250 NM, 55° SPACE STATION ORBIT



(B) FROM 250 NM POLAR SPACE STATION ORBIT

FIGURE 2. CONTOURS OF CONSTANT ONEWAY ΔV, INDICATING CIRCULAR ORBITS AT 250NM AND 800 NM WHICH ARE ACCESSIBLE FROM TWO SPACE STATION ORBITS BY TWO-BURN TRANSFER MANEUVERS (REFERENCE 4)

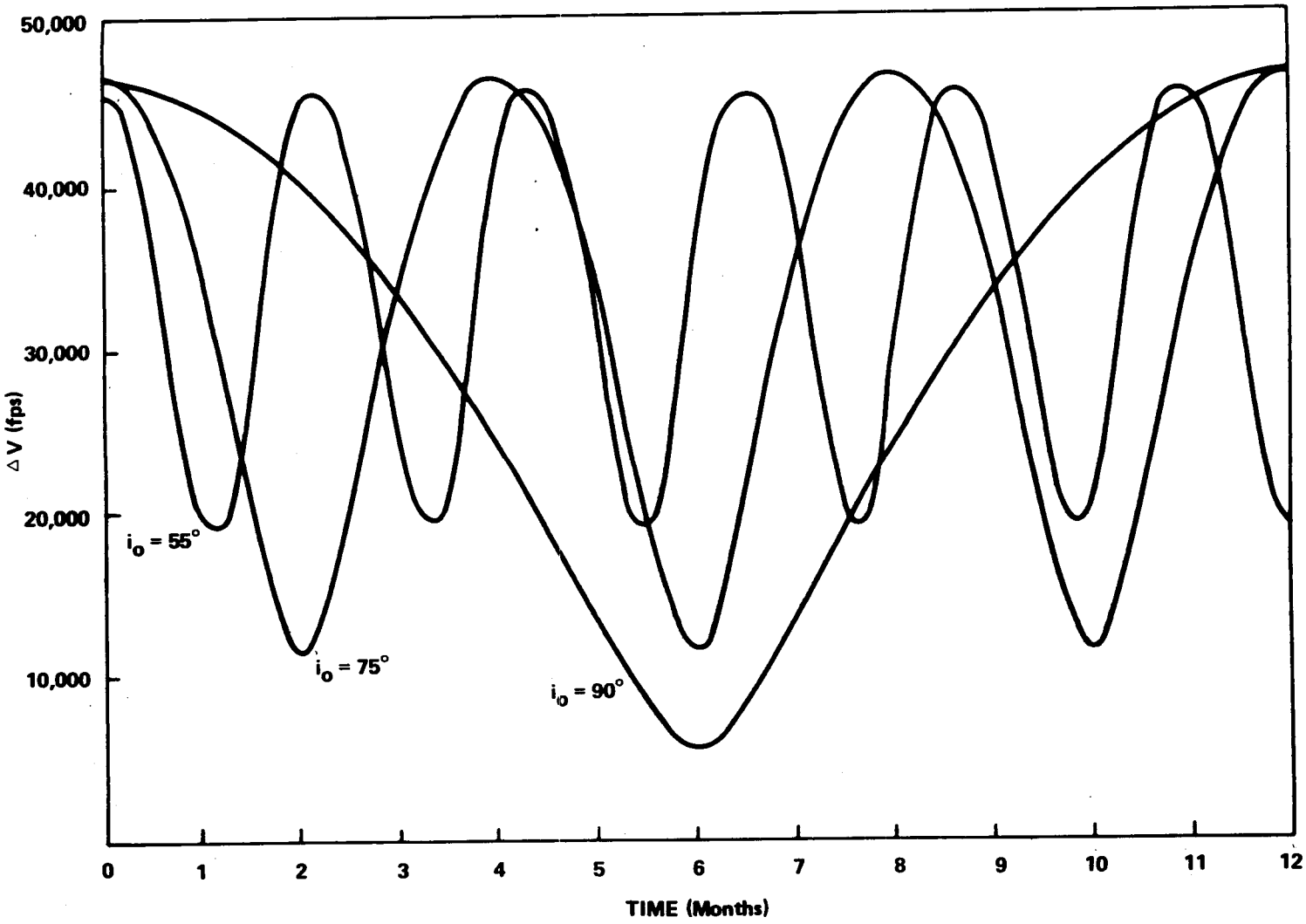


FIGURE 3. TIME VARIATION OF ΔV REQUIREMENT FOR TRANSFER TO A TYPICAL SUN-SYNCHRONOUS ($i = 102°$, $h = 800$ nm) ORBIT FROM A 250 nm SPACE STATION ORBIT AT INCLINATION i_o. (REFERENCE 4)

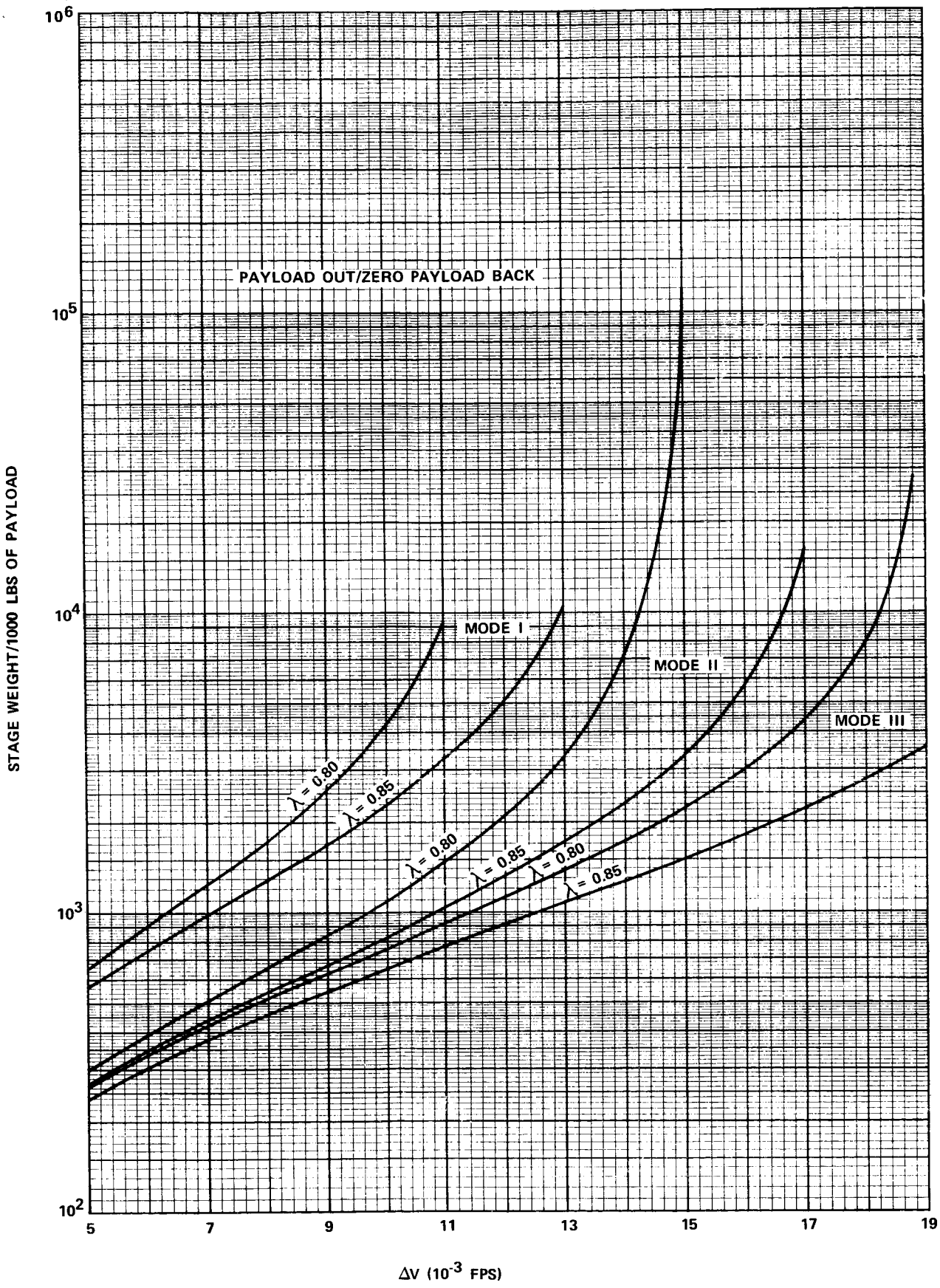


FIGURE 4 - SPACE TUG GROWTH FACTORS FOR PAYLOAD PLACEMENT
(ALL STAGES RECOVERABLE)

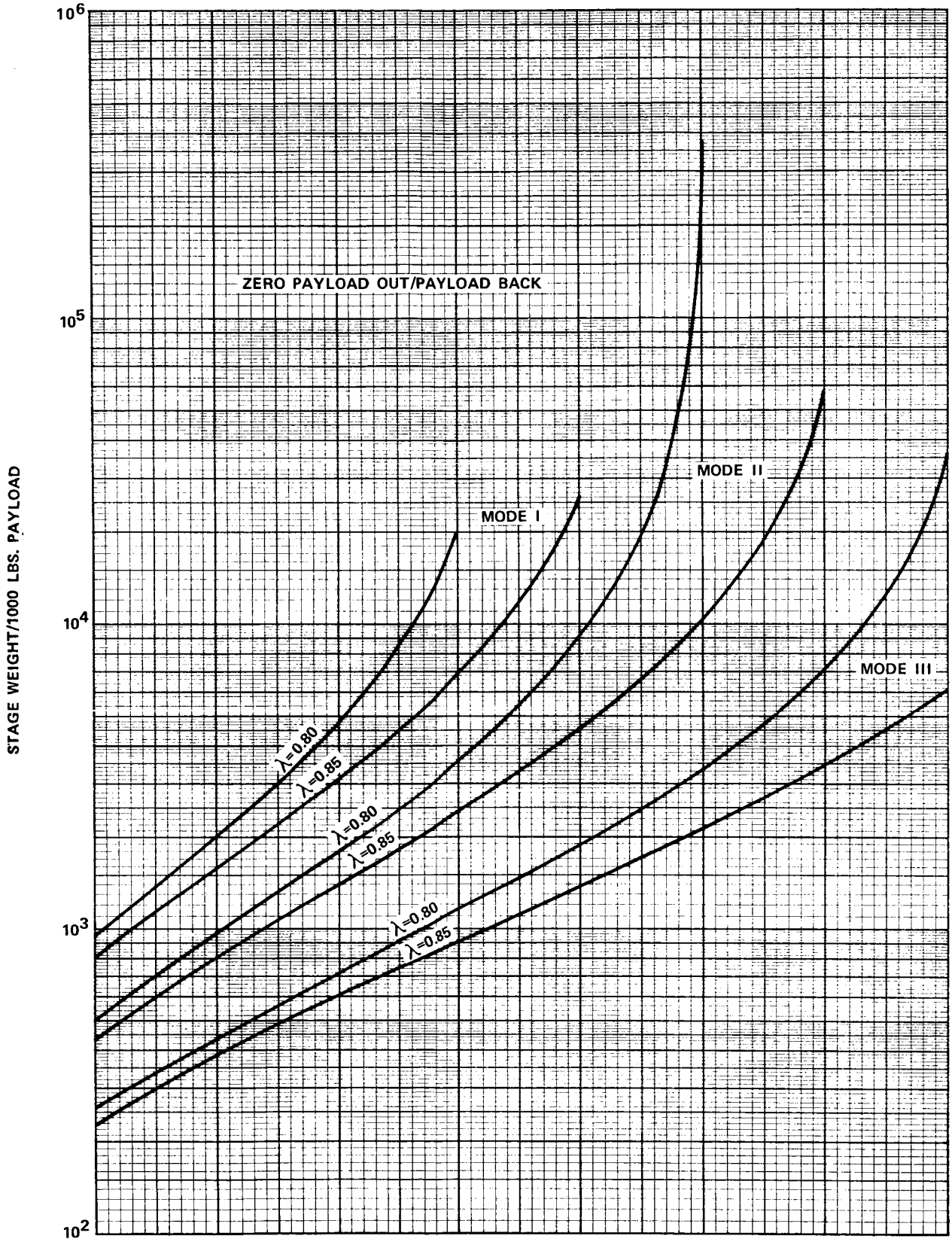


FIGURE 5 - SPACE TUG GROWTH FACTORS FOR PAYLOAD RETRIEVAL
(ALL STAGES RECOVERABLE)

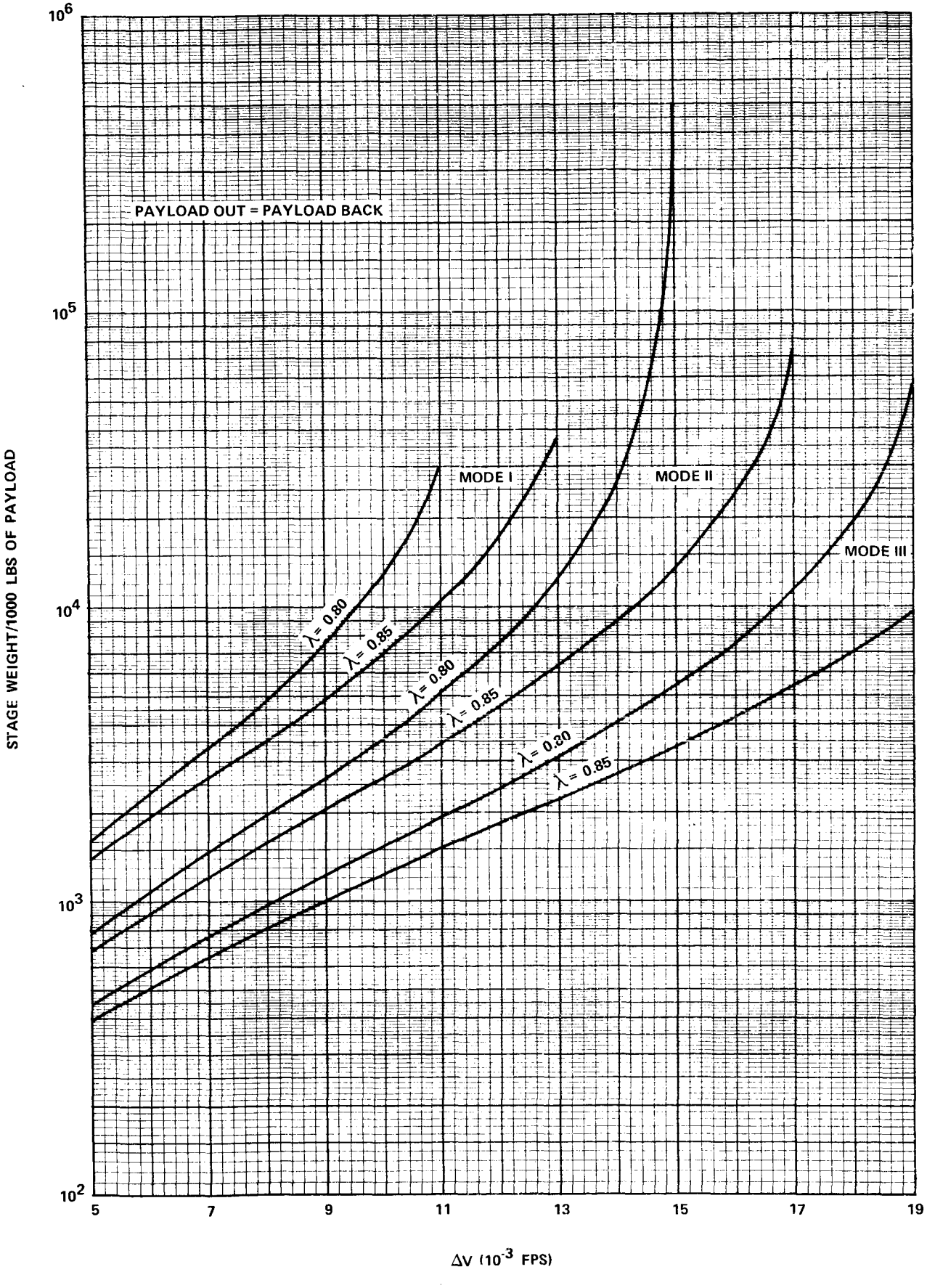


FIGURE 6 - SPACE TUG GROWTH FACTORS FOR ROUND TRIP PAYLOAD
(ALL STAGES RECOVERABLE)

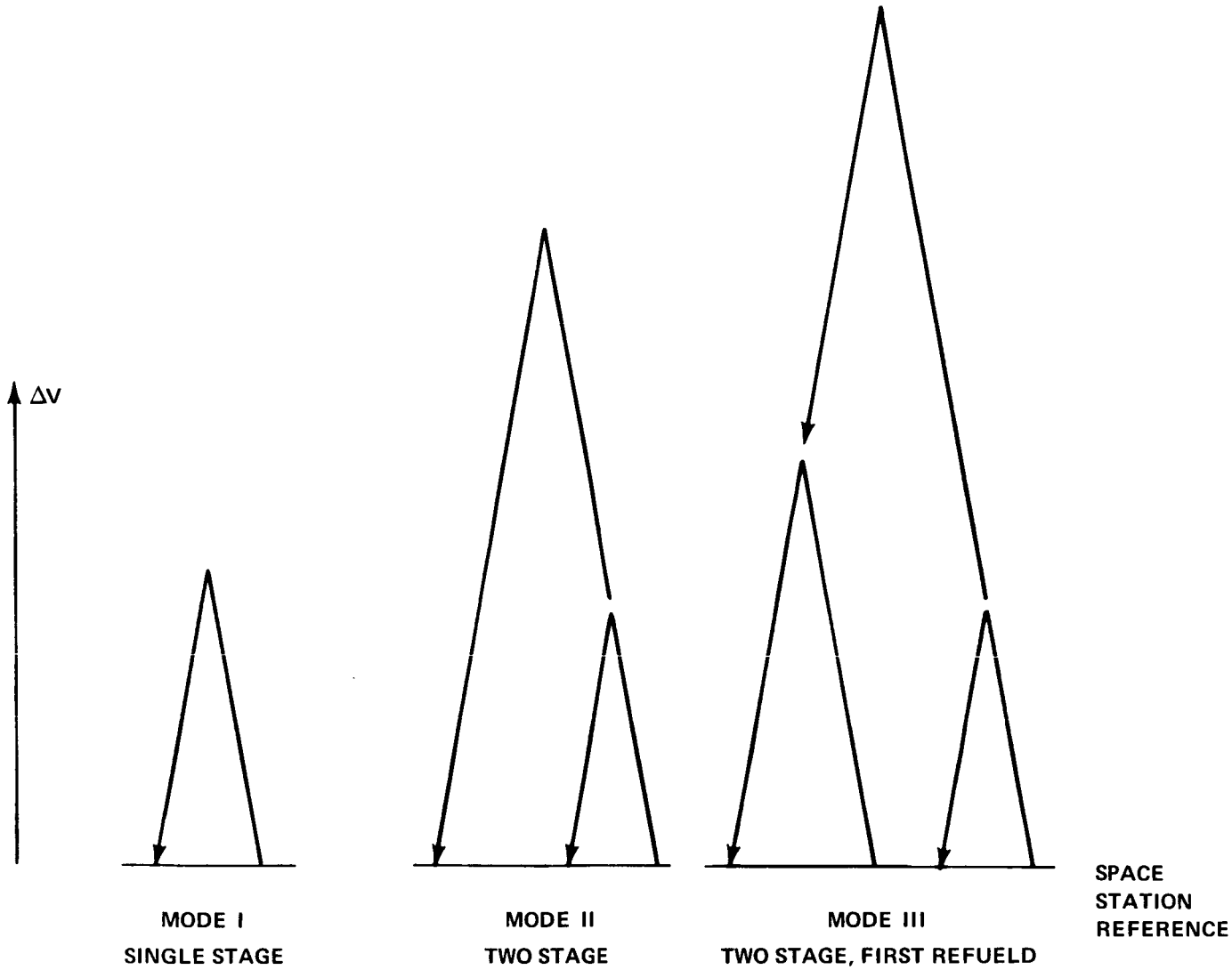


FIGURE 7 - EARTH ORBIT SATELLITE SERVICING MODES

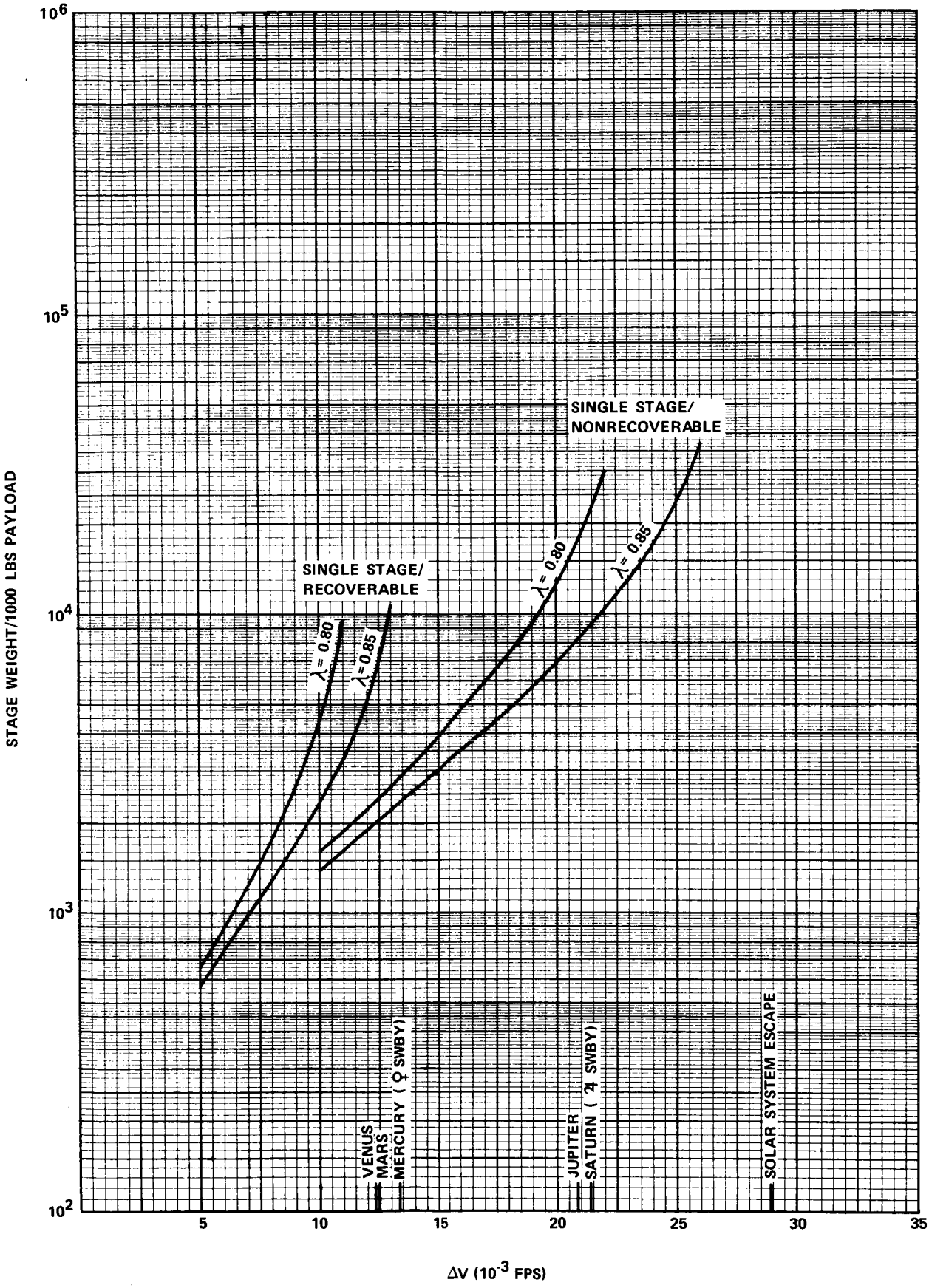


FIGURE 8 STAGE GROWTH FACTORS FOR REPRESENTIVE PLANETARY MISSIONS
SINGLE STAGE

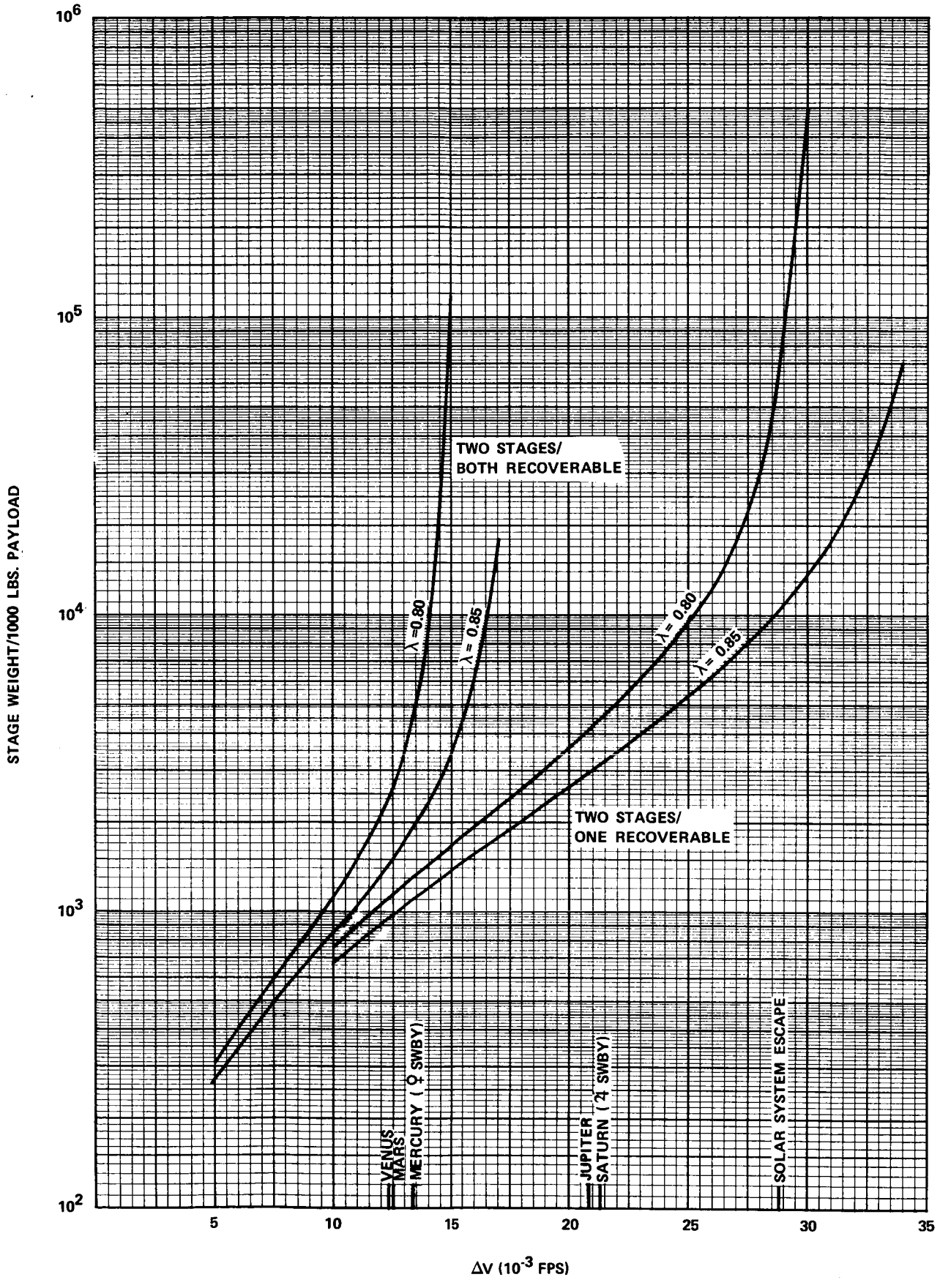


FIGURE 9 - SPACE TUG GROWTH FACTORS FOR REPRESENTATIVE PLANETARY MISSIONS

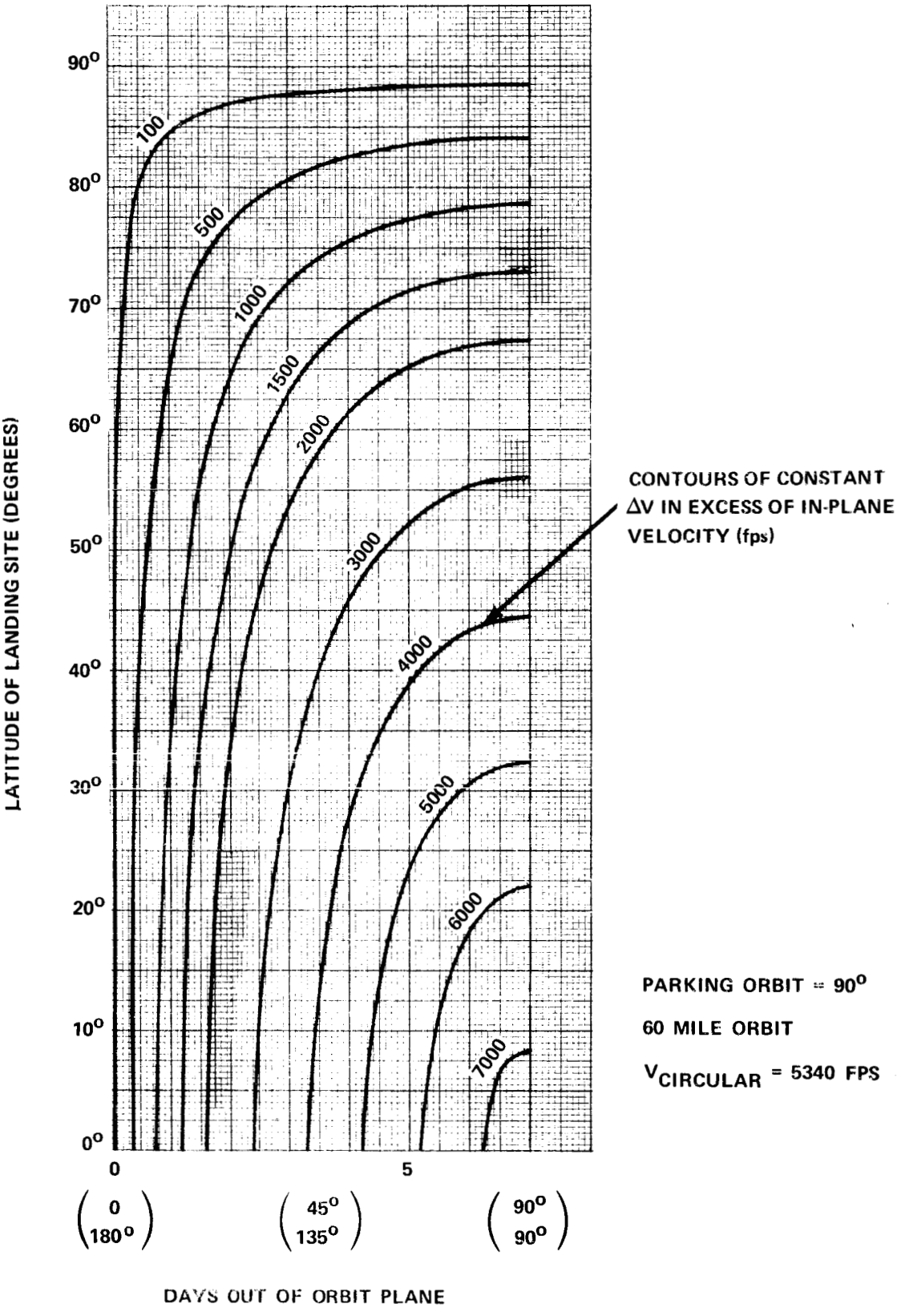


FIGURE 10 - PLANE CHANGE PENALTY FOR OUT-OF-PARKING-ORBIT-PLANE LAUNCH FROM LUNAR SURFACE TO LOW CIRCULAR POLAR ORBIT (REFERENCE 8)

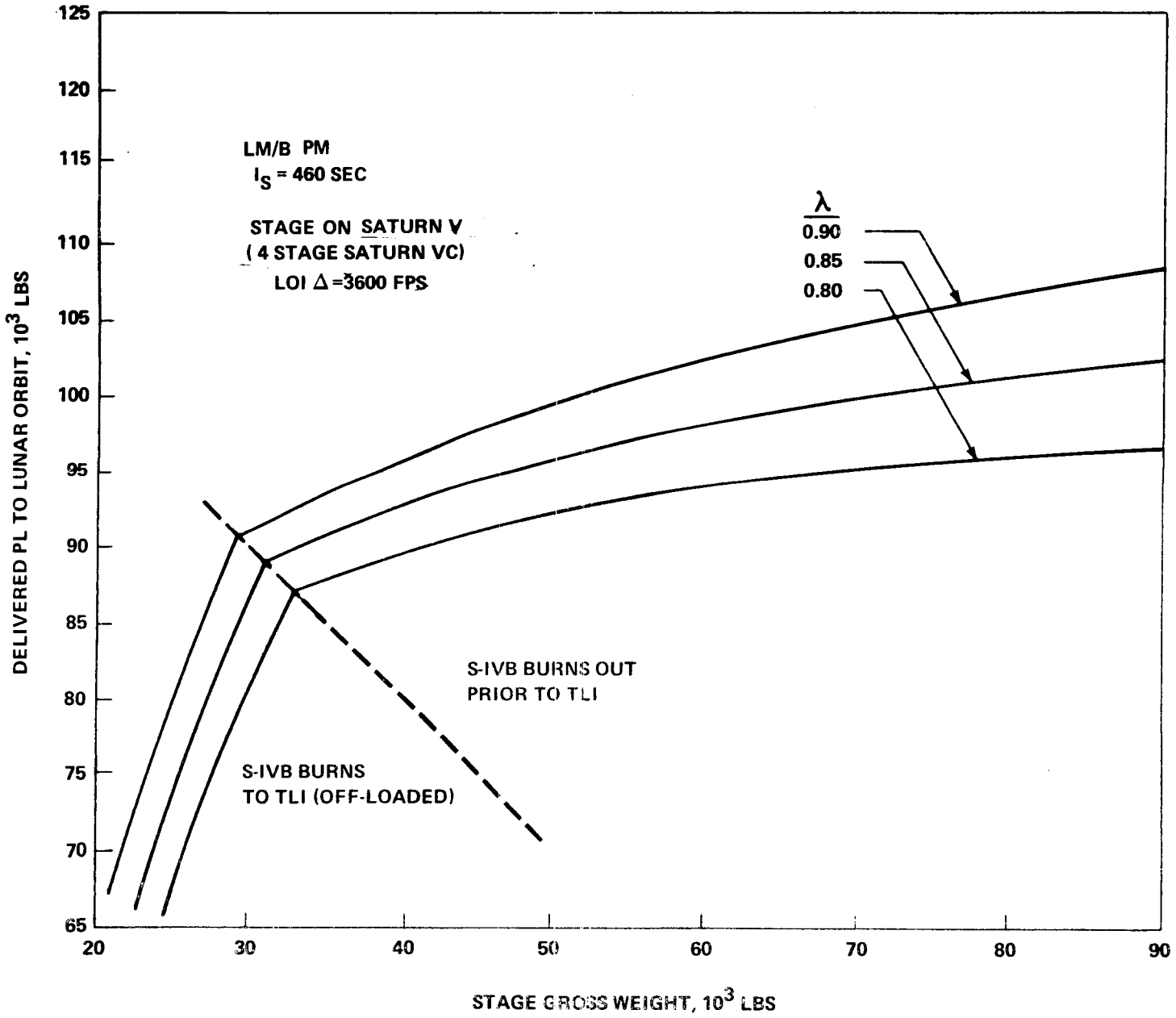


FIGURE 11 - DELIVERED PAYLOAD TO LUNAR ORBIT
4 STAGE SATURN VC (REFERENCE 9)

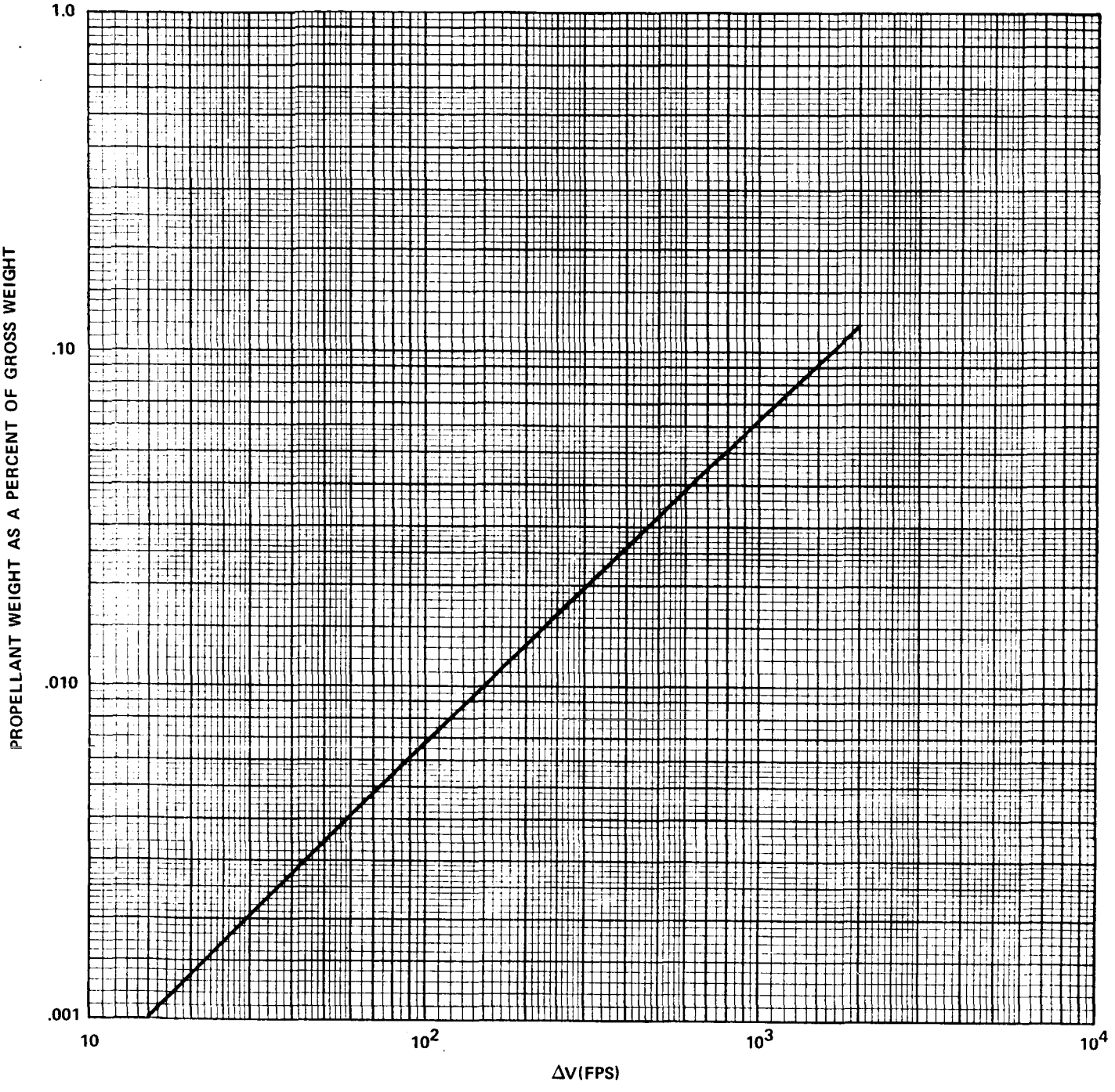


FIGURE 12 SPACE TUG PROPELLANT WEIGHT AS A FUNCTION OF GROSS WEIGHT (STAGE WEIGHT + PAYLOAD) FOR LOW ΔV MANEUVERS

BELLCOMM, INC.

Subject: Space Tug Operations in Association with the Integrated Program - Case 105-3

From: M. H. Skeer

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